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No. 3

THE VISIBILITY OF NOISE IN TELEVISION

by

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BRITISH BROADCASTING CORPORATION

FOREWORD

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PART I. THE VISIBILITY OF NOISE OVER THE GREY SCALE

1. *Introduction*

This paper attempts to clarify* certain effects produced upon the visibility of random fluctuation noise due to non-linearity in the relevant portions of television transmission channels.

A television transmission includes four basic elements; the scene to be transmitted (or an image of it), the television pick-up device, the receiving picture tube and the viewer's eye. In an ideal case we shall assume that the pick-up tube *transfer characteristic would be complementary to that of* the picture tube, so that there would be proportionality between the brightnesses of corresponding parts of the received image on the picture-tube screen and the original scene itself. Throughout what follows we shall retain the assumption that the transfer characteristic between the scene to be transmitted and its image on the receiver picture tube is linear. In some cases gamma-control circuits are required when the pick-up tube has a transfer characteristic which is not complementary to that of the picture tube. The effect produced by these gamma-correction circuits upon the visibility of the noise and particularly upon its distribution over the grey scale of the image has given rise to some confusion.

First, the effect produced by a non-linear circuit on the noise must be understood. The change in the power spectrum of the noise caused by its passage through a non-linear circuit will be ignored because it is considered to be negligible in most television applications. We assume that the noise fluctuation is so *small* that its waveform is unaltered by the non-linearity of the transfer characteristics which operate upon it; this is a corollary to the previous statement. When television signal and noise are simultaneously present in a non-linear circuit the noise may be regarded as 'riding upon' the signal in the manner shown in Fig. 1.† Two different signal levels S_1 and S_1' are shown accompanied by noise fluctuations N_1 and N_1' respectively. The figure shows that, although N_1' may have the same value as N_1, the output fluctuations N_2' and N_2 are by no means equal; they would be equal if the characteristic were linear.

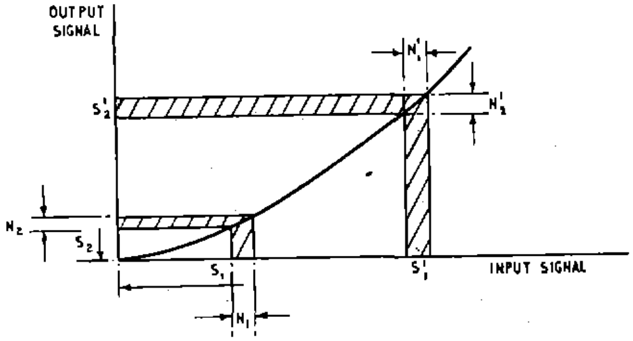

Fig. 1 — *Effect of non-linear circuit on signal and noise*

It is well known (Weber-Fechner law) that the function relating the sensation of brightness to the objective brightness of a patch of light is of a more or less logarithmic form. Furthermore, for many practical purposes it may be taken as a simple power law or gamma characteristic. Fig. 2‡ shows this function plotted over a range of brightness commensurate with that found in typical television reception conditions. This curve expresses a relationship which is very close indeed to that which would describe the sensation of brightness as being proportional to the cube root of the objective brightness.

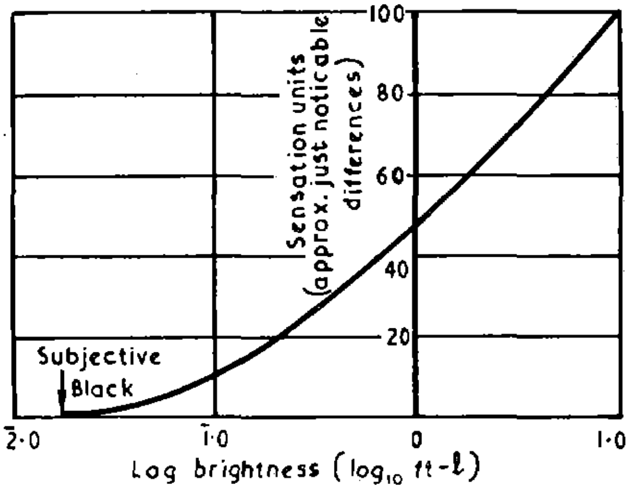

Fig. 2 — *Sensation scale for the eye with a surround brightness of* 1 *ft-l*

It so happens that the normal receiver picture tube has a transfer function relating screen brightness to grid voltage which approximates to a simple five-halves power law, and as this is almost complementary to the eye characteristic we may conclude that the transfer law between (subjective) sensation and picture-tube grid voltage is nearly linear or unity gamma. Thus, as pointed out by Kell[1], equal increments of picture-tube grid voltage give rise to equal increments of sensation. It may be stated quite generally that any noise fluctuation added to the signal before its arrival at the picture-tube grid and subsequent to any non-linear circuits employed at the point of origin will appear to be evenly distributed over the grey scale of the received image. The noise produced by the first stage of the receiver as well as that introduced in the process of transmission come within this category. There are several cases in which noise originating at the television pick-up device also comes within the same category. Fig. 3 shows a schematic diagram of a typical example, in which an iconoscope or image iconoscope camera tube requiring no gamma correction sends picture signals through a linear television channel to the grid of a receiving picture tube. No gamma correction is necessary because quite fortuitously the camera-tube transfer function expressing signal current in terms of scene brightness (light input) approximates to a two-fifths power law which is complementary to the picture-tube characteristic: in this way brightness linearity from scene to receiver-screen image is maintained. Excluding fringe-area reception, the greater part of the noise visible at the reception of picture signals originating from a source such as is shown in Fig. 3 arises in the first valve in the camera head amplifier and, from what has been said, will appear to be equally visible throughout the grey scale of the received image. Experience has shown that this is, in fact, the case. The transfer functions of the various high-velocity-beam cameras and receiving cathode-ray tubes are well known; only the eye characteristic is open to question. The fact that in a transmission such as that indicated in Fig. 3 the noise does seem to be evenly distributed over the grey scale may, however, be regarded as confirming the general shape of the curve in Fig. 2.

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* For a more detailed discussion the reader is referred to Schade, O. H., *Image Gradation, Graininess and Sharpness in Television and Motion Picture Systems*. Journal of Soc. of Motion Picture and Television Engineers, August, 1953.

† Vide Schade, O. H., *Electro-Optical Characteristics of Television Systems*, (*Fig.* 44). R.C.A. Review, September, 1948.

‡ This curve is deduced from Fig. 16 of *Colour Reproduction by Colour Photography*, F.I.A.T. Final Report No. 977 (H.M.S.O.). It is similar to curves quoted by L. A. Jones, Phot. Journal, 89B/131/1949, and R. G. Hopkinson, Phot. Journal, 91B/4/1951.

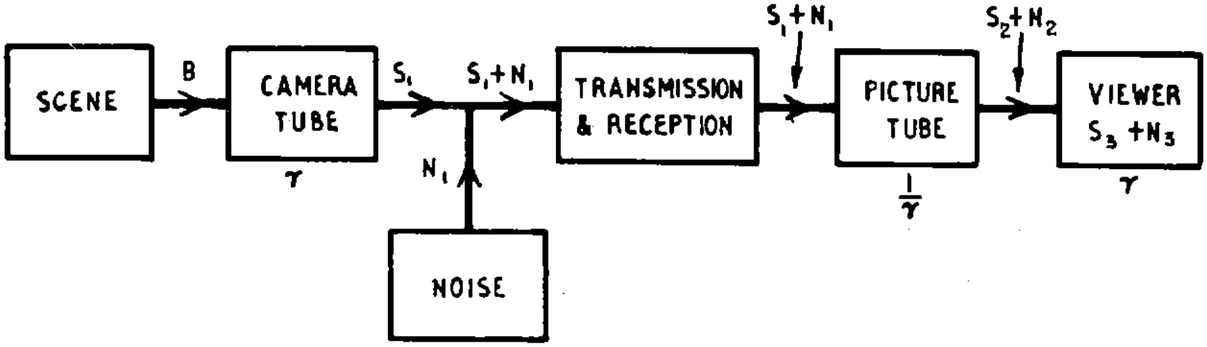

Fig. 3 — *Television transmission using high-velocity camera*

From the foregoing it will be evident that the distribution of noise visibility depends upon the position at which the noise is inserted, the camera-tube characteristic and other factors. It will be assumed in what follows that the uniform distribution of noise visibility is the least undesirable way of presenting noise in a picture containing brightness levels within contrast ranges typical of television. Kell's experiments[1] would seem to verify this assumption.

The often-heard phrase 'gamma circuits introduce noise', whilst not meant to be taken literally, nevertheless tends to remove from a picture source the onus of responsibility for a poor operating signal-to-noise ratio which remains concealed until revealed by a gamma-correction circuit. The latter may well be necessitated by considerations of picture 'tone' gradation rather than signal-to-noise ratio.

To illustrate this point, consider the case of a low-velocity-beam camera such as the orthicon, Fig. 4, for which the transfer characteristic is linear. As in the previous example, first-stage noise is added after the signal leaves the camera tube, but its visibility over the grey scale will in this case be different. The signal from the camera tube is no longer proportional to the sensation of scene brightness; for it to be so, we should require a camera tube transfer characteristic having a two-fifths (or better, a one-third) power law. If, therefore, we re-plot this transfer characteristic as signal current against scene brightness in sensation units, it will have the form of a five halves (or better, a cube) law and will be relatively insensitive in the 'blacks' and too sensitive in the 'whites'. A noise fluctuation added to the output signal will thus 'disturb' the signal in the darker tones to a much greater extent than it will in the lighter tones. This will not be apparent if the picture is viewed directly on a normal picture tube, simply because the darker tones, and the noise, will be crushed. The gamma-correcting circuit which is necessary in order to compensate for the picture-tube characteristic merely reveals a situation which exists at the camera output. Thus, a camera tube having a transfer characteristic which differs from that of the human eye (a one-third to two-fifths power law) will always give rise to the sensation of unequally distributed noise, if the latter is added after the camera tube. If the camera tube transfer characteristic has a higher power than that of the eye then noise will be more apparent in the 'blacks' whilst a lower power law will cause it to be more visible in the 'whites'. An extension of this discussion will perhaps reveal the camera's responsibility more clearly. Suppose we invent a linear cathode-ray tube, that is, one in which the screen-brightness is propor-

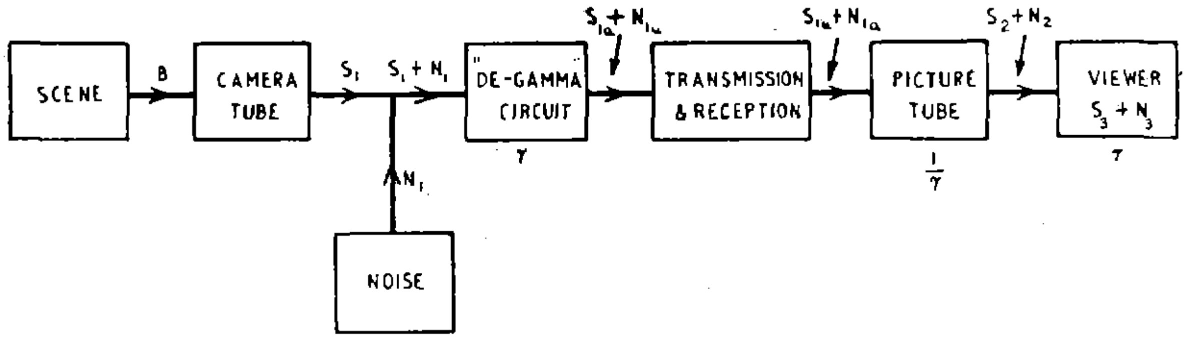

Fig. 4 — *Television transmission using low-velocity orthicon-type camera*

tional to the grid voltage. This tube used in conjunction with a linear camera tube such as the orthicon will no longer require a gamma-correction circuit and yet, in spite of the absence of gamma correction, the sensation of noise will still be predominant in the 'blacks'. Thus, it is seen that the gamma-correction circuit merely compensates for a non-linear cathode-ray tube and has no influence upon the distribution of the sensation of noise over the grey scale.

It might be remarked that notwithstanding the high (but in practice never infinite) gain at low brightness or signal levels introduced by the de-gamma circuit, if the noise level were sufficiently low* it would scarcely be visible, particularly as the sensitivity of an orthicon-type camera measured in terms of μA/lumen is greater than that of the image iconoscope. Fig. 5[2] will elucidate this point. Curve 1 is the transfer characteristic of an image iconoscope whilst Curve 2 is that of an orthicon-type camera type. It will be seen that for a given luminous flux on to the photocathode and target respectively, the orthicon-tube is the more sensitive type and since we assume the same head amplifier, and therefore noise level, for the two tubes, the signal-to-noise ratio of the orthicon-type is greater. Unfortunately it is not possible to reap the full benefit of the orthicon's greater sensitivity because of target instability or 'peel-off'. This phenomenon occurs when the incident light flux on to the target exceeds a threshold value and thus limits the permissible amount of studio lighting to a value such that the flux arriving on the target from the brightest part of the scene does not exceed that required by the point A′ in the figure. If the contrast ratio it is desired to transmit is, say, ten to one, then the 'blackest black' will be represented by the point B′ and this will give rise to a signal current of about 0·007μA. Now to transmit the same scenic contrast range with an image iconoscope requires an altogether higher level of studio lighting, but this can easily be accomplished and gives us the operating points A and B. In this case the current corresponding to the 'blackest black' will be 0·019μA and the signal-to-noise ratio in the blacks will be two and a half times that obtained in the 'dimmer' scene required for the orthicon-type tube.

The above discussion, whilst not directly relevant to a study of the distribution of the noise over the grey scale, nevertheless points to the conclusion that, in the presence of an *upper limit* to scene brightness, a linear camera-tube characteristic is not necessarily desirable—nor would it become so if cathode-ray tubes had linear transfer characteristics because the low-gamma characteristic of the eye would still intervene to raise the visibility of the noise in the 'blacks'.

The above discussion in qualitative terms will now be followed by quantitative analyses of several practical cases.

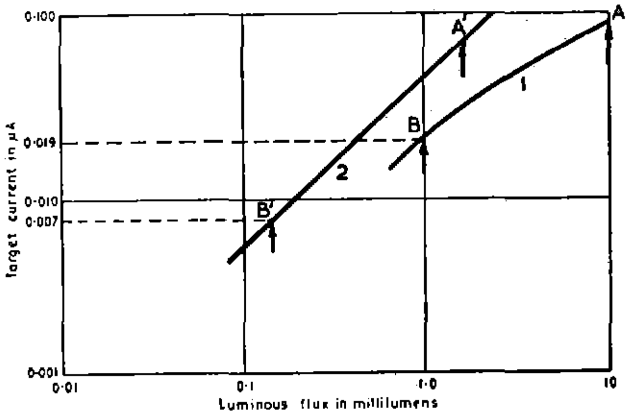

Fig. 5 — *Comparison between cameras with linear and non-linear transfer characteristics*

2. Use of Camera with High-velocity Beam

Let us consider a typical transmission using a high-velocity camera having a simple power-law transfer characteristic relating output signal to input luminance. Let us assume also that the receiver picture-tube transfer characteristic is likewise a simple power law having as its exponent the reciprocal of that of the camera tube; and lastly we shall take the transfer characteristic of the viewer's eye relating sensation units in the brain to luminance on the picture-tube screen to be the same as that of the camera tube. Fig. 3 shows the sequence of processes through which the signal and the noise arising in the first valve of the camera head amplifier will pass.

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* In an unpublished communication, Dr E. L. C. White of E.M.I. has pointed out to the author that a 7 db gain in signal-to-noise ratio can be obtained by the insertion of inductance between signal plate and head amplifier according to a method proposed by James, I. J. P., *Fluctuation Noise in Television-Camera Head Amplifiers*. Proc. I.E.E., Pt IIIA, No. 20, p. 796, 1952.

Let B $\propto$ scene brightness
S_1 $\propto$ signal emerging from camera tube
N_1 $\propto$ noise added to camera-tube output, that is, noise added to S_1
S_2 $\propto$ signal brightness on picture-tube screen
N_2 $\propto$ noise brightness on picture-tube screen
S_3 $\propto$ sensation units of signal brightness in the eye
N_3 $\propto$ sensation units of noise brightness in the eye

Fig. 3 shows that, in the absence of noise

$$S_1 \propto B^{\gamma},\ S_2 \propto S_1{}^{1/\gamma} \text{ i.e. } S_2 \propto B, \text{ and } S_3 \propto S_2{}^{\gamma} \text{ i.e. } S_3 \propto B^{\gamma} \,..\,(1)$$

If we now assume that in each section of the signal chain the noise is always much smaller in amplitude than the signal, we may write

$$N_1 \ll S_1 \quad N_2 \ll S_2 \quad N_3 \ll S_3 \ldots\ldots\ldots\ldots (2)$$

and the action of the gamma circuits on the signal will be unaffected by the presence of relatively small noise components; furthermore, these may be treated as differentials.

Fig. 1 shows what becomes of a signal S_1 and its attendant noise or uncertainty N_1 when these are passed simultaneously through a non-linear circuit described by one of the proportionalities 1, say

$$S_2 \propto S_1{}^{1/\gamma}$$

It is easy to see that the output noise N_2 may be obtained either directly by multiplying the input noise by the slope or derivative of the gamma curve at that point which is determined by the level of the input signal, S_1, or by raising the input consisting of noise and signal to the appropriate power (e.g. $1/\gamma$) required by the exponent of the succeeding non-linear device, and then neglecting all terms other than the first two; that is, obtaining noise and signal but neglecting terms containing noise raised to powers higher than the first. Thus, using the derivative method

$$N_2 \propto N_1 \frac{dS_2}{dS_1} \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

and similarly, the subjective effect of the noise in sensation units will be

$$N_3 \propto N_2 \frac{dS_3}{dS_2} \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

If we substitute into proportionalities 3 and 4 those obtained from 1 and substitute into 4 the value of N_2 from 3 we obtain

$$N_3 \propto N_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

This is a result of some importance, for it shows that, for the particular case we are considering, the noise sensation is independent of signal level or scene brightness. If the noise does not depend upon scene brightness it must appear as evenly distributed throughout the contrast range of the picture-tube image as stated in the Introduction.

It has already been said that this state of affairs occurs when high-velocity cameras are used. This proves that the non-linear transfer characteristic of the eye (sensation units/image brightness) must approximate to that of a high-velocity camera for which, as is well known, $\gamma \simeq 2/5$.

3. Use of Camera with Low-velocity Beam: Orthicon-Type Camera

It is now possible to show in a simple manner how the noise in a viewed image originated by a low-velocity orthicon-type camera seems more perceptible in dark regions than elsewhere. In the Introduction it was explained why, in view of the greater sensitivity of the orthicon, the noise is not entirely negligible as might have been supposed.

Fig. 4 shows a typical television transmission using an orthicon-type camera. The noise due to the first valve in the head amplifier is added to the signal before the latter has suffered any non-linearity and thus combines with the signal at a part of the chain in which equal increments of excitation do not give rise to equal increments of sensation.

Let B $\propto$ scene brightness
S_1 $\propto$ signal emerging from camera tube
N_1 $\propto$ noise added to camera-tube output, that is, noise added to S_1
S_{1_a} $\propto$ signal output from de-gamma circuit
N_{1_a} $\propto$ noise output from de-gamma circuit
N_2 $\propto$ noise brightness on picture-tube screen
S_2 $\propto$ signal brightness on picture-tube screen
S_3 $\propto$ sensation units of signal brightness
N_3 $\propto$ sensation units of noise brightness

This time we have, in the absence of noise,

$$S_1 \propto B,\ S_{1_a} \propto S_1{}^{\gamma}, \text{ i.e. } S_{1_a} \propto B^{\gamma},\ S_2 \propto S_{1_a}{}^{1/\gamma}, \text{ i.e. } S_2 \propto B, \textit{ and } S_3 \propto S_2{}^{\gamma}, \text{ i.e. } S_3 \propto B^{\gamma} \ldots\ldots\ldots\ldots (6)$$

Assuming again that the noises are small compared with their attendant signals we have

$$N_{1_a} \propto N_1 \frac{dS_{1_a}}{dS_1} \ldots\ldots\ldots\ldots\ldots (7)$$

$$N_2 \propto N_{1_a} \frac{dS_2}{dS_{1_a}} \ldots\ldots\ldots\ldots\ldots (8)$$

$$N_3 \propto N_2 \frac{dS_3}{dS_2} \ldots\ldots\ldots\ldots\ldots (9)$$

Substituting the appropriate proportionality from 6 into 7, 8 and 9, and then substituting 7 into 8 and 8 into 9 we obtain

$$N_3 \propto \frac{\gamma N_1}{B^{1-\gamma}} \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

If we let $\gamma = 2/5$ which we know to be a reasonable approximation, proportionality 10 yields

$$N_3 \propto \frac{N_1}{B^{3/5}} \dots\dots\dots\dots\dots\dots (11)$$

This shows that when using an orthicon-type camera followed by a de-gamma circuit in the camera control unit, the noise will be a function of the scene brightness B, and will be most evident in the 'blacks'. This is, in fact, the case.

If it were desirable and convenient to de-gamma the scene itself or at least its electronic image on the orthicon target then the situation would become the same as that described in the case of high-velocity-beam cameras, and the de-gamma circuit which had been situated after the point at which the noise was added could be removed. The noise would then appear to be uniformly spread over the entire grey scale.

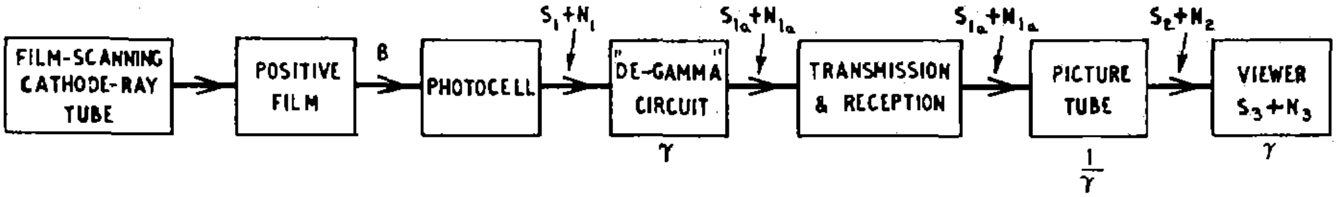

Fig. 6 — Television transmission with film scanner using high-gain photomultiplier

4. Use of Film Scanner with High-gain Photomultiplier[3]

Fig. 6 is a schematic diagram showing the processes through which the signal and noise must pass. The effect of noise due to afterglow has been omitted from this discussion. It may be seen that, using similar notation to that in Section 3 and where B is scene brightness and transmission of the positive film,

$$S_1 \propto B,\ S_{1_a} \propto S_1^{\gamma} \text{ i.e. } S_{1_a} \propto B^{\gamma},\ S_2 \propto S_{1_a}^{1/\gamma} \text{ i.e. } S_2 \propto B,\ S_3 \propto S_2^{\gamma} \text{ i.e. } S_3 \propto B^{\gamma} \dots\dots\dots (12)$$

Now the type of photocell used has a high-gain electron multiplier built into its envelope and, neglecting dark current, the noise power is proportional to the incident light flux which is, in turn, proportional to the film transmission of scene brightness, B. The r.m.s. noise is therefore proportional to $\sqrt{B}$. Thus we have

$$N_1 \propto B^{1/2} \dots\dots\dots\dots\dots\dots (13)$$

Substituting proportionalities 12 and 13 into 7, 8 and 9, we find that

$$N_3 \propto \gamma\, B^{\gamma-1/2} \dots\dots\dots\dots\dots (14)$$

If we let $\gamma = 2/5$ we see that N_3 is nearly constant, that is, the noise sensation is almost uniformly distributed over the grey scale as it was in the case of the high-velocity camera, although from different causes.

It is interesting to examine the behaviour of the noise when the same film scanner is used to transmit from negative film as distinct from positive. In this case the negative film may be assumed to have a gamma of about $-0{\cdot}7$. Fig. 7 shows the processes through which the signal and noise must pass in this case. With the notation shown in the figure we have, if B is the original scene brightness, $S_0 \propto B^{-0\cdot7}$, $S_1 \propto S_0$ i.e. $S_1 \propto B^{-0\cdot7}$, $S_{1b} \propto S_1^{-\gamma/0\cdot7}$ i.e. $S_{1b} \propto B^{\gamma}$, $S_2 \propto S_{1b}^{1/\gamma}$ i.e. $S_2 \propto B$, $S_3 \propto S_2^{\gamma}$ i.e. $S_3 \propto B^{\gamma} \dots\dots (15)$ and, similarly to proportionalities 7, 8 and 9,

$$N_{1b} \propto N_1 \frac{dS_{1b}}{dS_1} \quad N_2 \propto N_{1b} \frac{dS_2}{dS_{1b}} \quad N_3 \propto N_2 \frac{dS_3}{dS_2} \dots\dots\dots (16)$$

Substituting 13 and 15 into 16 we obtain

$$N_3 \propto -(\gamma/0{\cdot}7)\, B^{\gamma+6/5} \dots\dots\dots\dots (17)$$

If we let $\gamma = 2/5$ we see that the noise sensation is proportional to the eight-fifths power of the scene brightness. This may be a serious disadvantage in the use of direct-negative transmissions; the noise would be highly concentrated towards the 'white' end of the grey scale.

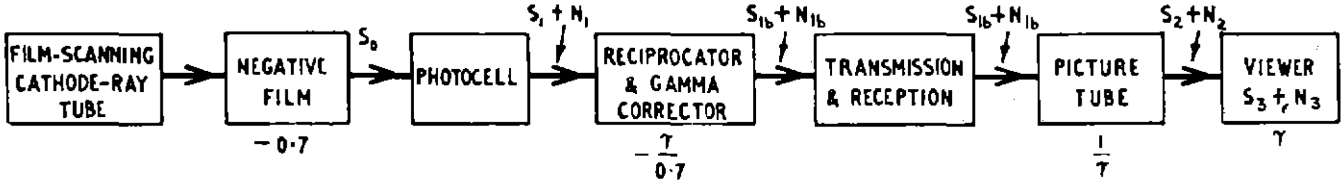

Fig. 7 — Television transmission from negative film with film scanner using high-gain photomultiplier

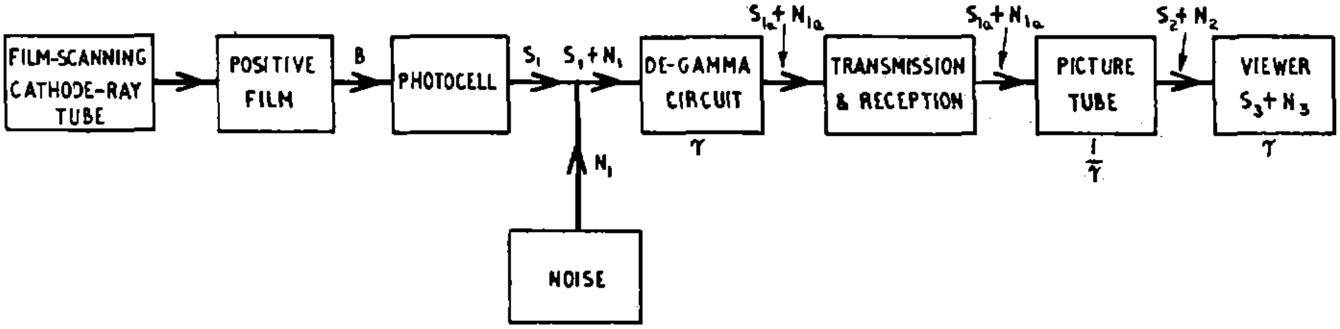

Fig. 8 — *Television transmission with film scanner using low-gain photocell*

5. Use of Film Scanner with Low-gain Photocell[4]

Fig. 8 shows that for this type of photocell we regard the noise as originating entirely in the first stage of the head amplifier and thus assume that it is independent of signal or brightness level. This is by no means strictly true but will supply us with characteristics quite distinct from the case just treated in which we assumed the noise to be entirely dependent upon brightness. The practical case will lie between these two examples. Fig. 8 shows that this case is identical with that of the low-velocity camera treated in Section 3. It will be recalled (proportionality 11) that the noise sensation in that example increased in the 'blacks'. As was stated in the last paragraph of Section 3, the noise visibility could be rendered less obtrusive by applying de-gamma technique to the scene. In the case of film scanners, however, this would be quite possible although requiring non-standard film. Satisfactory results would be obtained with positive film having a two-fifths gamma law.

The case of transmission from negative film is shown in Fig. 9. Using proportionalities 15 and 16 and remembering that, as in Section 3, N_1 is independent of B, we have

$$N_3 \propto \frac{-\gamma N_1}{0\cdot7} B^{\gamma+0\cdot7} \ldots\ldots\ldots\ldots\ldots (18)$$

If $\gamma = 2/5$ we find that the noise sensation is proportional to the eleven-tenths power of the brightness, which, although undesirable, is more evenly distributed than was the noise sensation when using a film scanner employing a high gain multiplier-type photocell for transmission from negative film. This may explain the superiority of the low-gain-photocell type of film scanner over the high-gain-photomultiplier model for direct-negative transmission.

6. Use of Camera with Low-velocity Beam: Image-orthicon Camera[5]

This case must be regarded as very tentative because the operation of image-orthicon cameras depends greatly on electron-image re-distribution effects which convert a saturated static gamma characteristic into what amounts to a dynamic characteristic having an exponent of about 2/5. Let us assume, as seems probable, that the two-fifths power law which operates on the scene-brightness to charge-image transfer characteristic does not directly affect the noise in that the latter, being due to 'shot' effect in the return scanning beam, is proportional to the half-

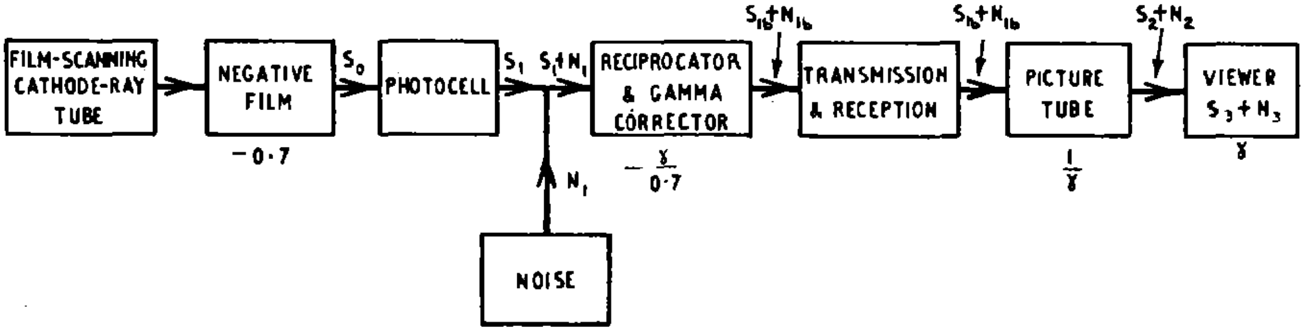

Fig. 9 — *Television transmission from negative film with film scanner using low-gain photocell*

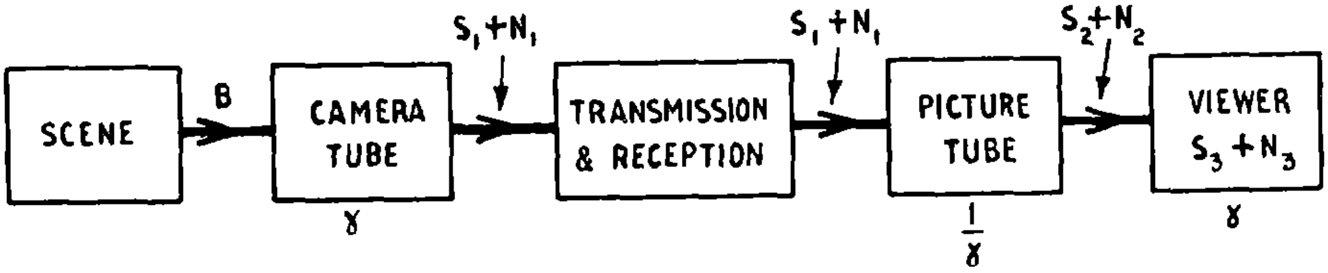

Fig. 10 — Television transmission using low-velocity image-orthicon camera

power of the return-beam current. The signal-modulated beam current may itself be assumed to vary as the two-fifths power of the scene brightness.

Referring to Fig. 10 and using the notation shown there, we have, omitting reference to signal polarity,

$$S_1 \propto B^{\gamma},\ S_2 \propto S_1^{1/\gamma} \text{ i.e. } S_2 \propto B \text{ and } S_3 \propto S_2^{\gamma} \text{ i.e. } S_3 \propto B^{\gamma} \ldots (1)$$

wherein we have let γ be representative of the approximate two-fifths power law between scene brightness and camera output; and, remembering that the noise is due to the return beam only,

$$N_1 \propto (1-mS_1)^{1/2} \text{ or } N_1 \propto (1-mB^{\gamma})^{1/2} \ldots\ldots (19)$$

where m is the depth to which the return beam is modulated by the signal current.

Putting 1 and 19 into 3 and 4 we find that

$$N_3 \propto (1-mB^{\gamma})^{1/2} \ldots\ldots\ldots\ldots\ldots (20)$$

If we let $m=1/2$, $\gamma=2/5$ we find that the noise sensation increases very slightly towards the dark parts of the scene. From a practical viewpoint the noise may be regarded as uniform over the grey scale in that it varies by $\sqrt{2}$ to 1 in sensation units from black to white.

7. Conclusions

A number of television channels have been examined and the following conclusions may be drawn:

(i) Unity-gamma pick-up devices, whether they be cameras or film scanning equipment, distribute the sensation of noise unevenly over the 'tone' range of the picture unless the de-gamma device required to ensure correct 'tone' reproduction can be placed in the initial light path and thus precede the noise. This conclusion is restricted to picture-originating equipment in which the noise is added to the picture signal in such a way as to be independent of it at the place of addition. Orthicon-type cameras and flying spot film scanners with low-gain photocells are examples to which this conclusion is applicable.

(ii) Greater sensitivity expressed in microampères per lumen does not assure superiority as regards signal-to-noise ratio. If a camera suffers from a restriction upon the total permissible studio lighting due, for example, to target instability, then another camera which has no such limitation can be illuminated to such a value as to ensure a signal-to-noise ratio superior to that of the former.

(iii) As a corollary to (i) it is possible to ensure uniform distribution of noise sensation in the case of a flying spot film scanner using a low-gain photocell by insisting upon the use of low-gamma ($\gamma \simeq 2/5$, say) positive film and removing the 'post noise' de-gamma circuit required for transmission of normal unity-gamma positive film.

(iv) Flying spot film scanners using high-gain photomultiplier tubes ensure a near-uniform noise sensation distribution and are therefore to be preferred to the other type, quite apart from the fact that they are capable of a higher overall signal-to-noise ratio. The former type of film scanner, however, transmits negative film (with appropriate negative-gamma circuits) with a distribution of noise sensation which is biased heavily towards the lighter 'tones' in the picture; that is, it is 'noisy in the whites'. A film scanner using a low-gain photocell will transmit negative film (again with appropriate negative-gamma circuits) with a better distribution of noise sensation. It will still be noisy in the whites, but relatively less so than in the case of a film scanner using a high-gain photomultiplier tube. It should be remembered, however, that as already mentioned the high-gain photomultiplier will give rise to a greater signal-to-noise ratio than will the low-gain photocell in spite of the more even noise distribution of the latter.

(v) The image orthicon camera is a unique case in that it generates its own noise and the distribution of noise sensation in the final picture is nearly uniform, being about $\sqrt{2}$ times greater in the 'blacks' than in the 'whites'.

8. Acknowledgment

The author is indebted to Mr G. G. Gouriet for much helpful discussion which stimulated the investigation.

9. Appendix

(Contributed by W. N. Sproson, M.A.)

Section 5 has dealt with a film scanner using a low-gain photocell, and a certain film scanner fits into this category fairly well. In this connection some measurements on tone reproduction and noise may be of interest. The measured overall transfer characteristic is shown in Fig. 11. This gives the relative brightness of the reproduced image against the relative transmission of the film. Using the sensation *vs.* brightness curve shown in Fig. 2 it is a simple matter to recalculate the transfer characteristic in the form of sensation units and this is shown in Fig. 12. It will be seen that fairly good linearity of tone reproduction is obtained, except that the near-black tones have been over-accentuated.

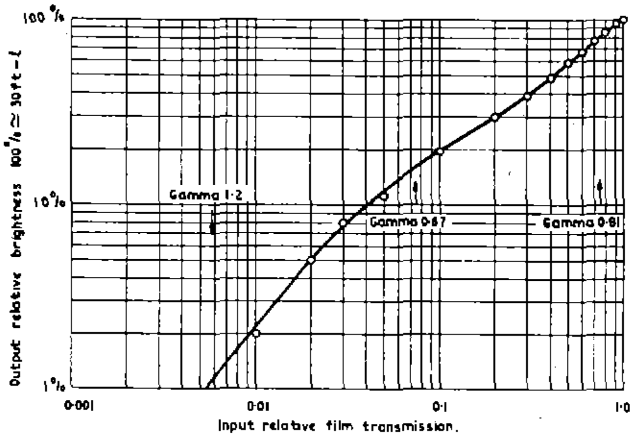

Fig. 11 — *Overall characteristic of Telecine (Photocell—gamma circuit—CRT)*

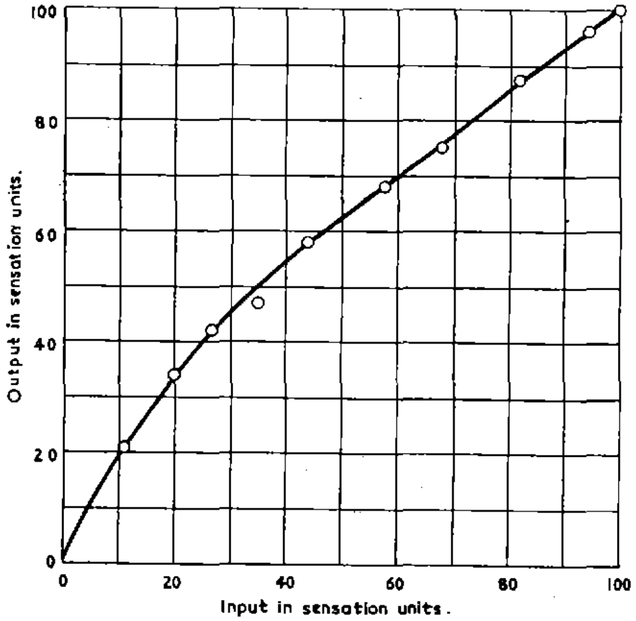

Fig. 12 — *Overall transfer characteristic of Telecine*

The effect of noise in this film scanner was estimated as follows: The noise level as displayed by a waveform monitor was measured at various signal levels: in actual fact the voltage excursions indicating noise were found to be approximately constant throughout the tone range from black to white. This constant voltage excursion applied to the cathode-ray-tube transfer characteristic and thence to the sensation curve (Fig. 2) gave a set of noise values in sensation units which have been plotted in Fig. 13. Although this curve has no simple mathematical equivalent, it is obvious that the noise in the 'blacks' is much more apparent than in the lighter tones, and is in general agreement with the result given by the simplified treatment in Section 5 of the main text.

It should be pointed out that Fig. 13 shows both scales in sensation units, i.e. both noise sensation and brightness sensation: in contradistinction the proportionalities evaluated in the main text quote noise in sensation units *vs.* brightness measured on an objective physical (non-sensation) basis.

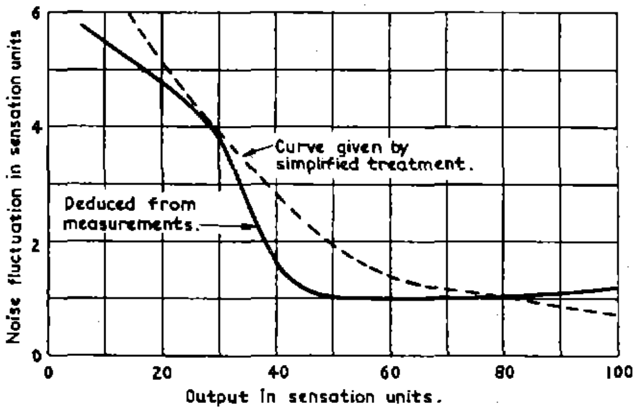

Fig. 13 — *Noise/output characteristics*

PART II

THE VISIBILITY OF NOISE AS A FUNCTION OF FREQUENCY

10. Introduction

One of the factors which will determine the quality of a picture transmitted over a television system and influence its acceptability is the signal-to-noise ratio. For a given signal-to-noise ratio, however, some types of noise may be more visible or more annoying than other types. The Post Office Engineering Department* have already investigated the relative visibility of three narrow frequency bands of noise taken from a random-noise generator, the three bands having mid-frequencies of 0·15 Mc/s, 1·66 Mc/s and 2·85 Mc/s.

It was decided initially to investigate the relative visibility of a number of narrow frequency bands of noise in the frequency range of 0 to 3·0 Mc/s, and to compare the results with the Post Office investigation. The ultimate aim of the investigation is to provide, if possible, a weighting network which will take into account the variation of visibility of different noise spectra and thus permit of direct objective measurement in terms of annoyance.

It should be pointed out that in these experiments, noise was added to the picture signal only, and had no influence on the synchronizing waveform. It would be desirable to continue the investigation later, by conducting experiments with noise of different spectral characteristics, such as noise with a triangular spectrum. Such further generalization should be of interest with reference to the quality of pictures originating from specific camera tubes, some of which give rise to noise spectra which are of triangular form.

11. Equipment

A noise-generator was designed to operate in the following manner:

The noise voltage appearing across the terminals of a 100,000 ohm resistor (Fig. 14) was fed to the input of a high-gain amplifier having a uniform response to frequencies between 0 and 500 kc/s. The output of the amplifier was used to modulate a 10 Mc/s carrier and the middle region of the resulting upper sideband was selected by a confluent band-pass filter with a pass-band of 10·1 to 10·4 Mc/s.

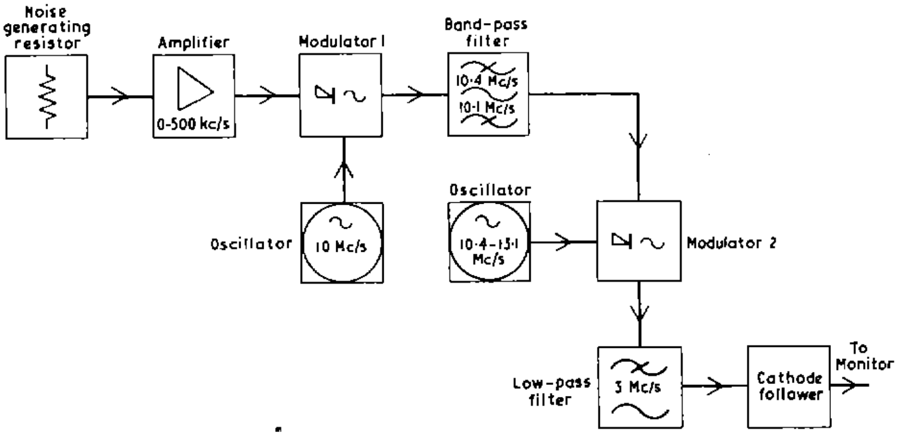

Fig. 14 — Block diagram of random noise generator

A balanced modulator multiplied this signal by the output of an oscillator of frequency variable from 10·4 to 13·1 Mc/s, thereby producing two bands of random noise, both 300 kc/s wide, the mid-frequencies of which were variable from 0·15 to 2·85 Mc/s and 20·65 to 23·35 Mc/s, respectively. A 3 Mc/s low-pass filter removed the upper band of noise, and the lower band was injected into a television camera channel, which, by itself, produced a substantially noise-free signal. It was thus possible to display narrow-band noise spectra, the mid-frequency of which could be continuously varied between 0·15 and 2·85 Mc/s. An attenuator between the apparatus described and the television channel enabled the noise level to be precisely controlled.

This method ensured that the interfering signal contained only random noise frequencies within the limits of the pre-selected 'window', but the validity of the results obtained by the method is in some doubt. There is no *a priori* reason for assuming that the annoyance value of a broad band of noise will be the same as the sum of the annoyance values of a number of smaller bands occupying the same total band-width. When a single narrow band of noise is added to a television picture, areas of 'pattern' are observed, and these are not a feature of broad band noise; this effect may be due to the increased probability of correlation between signals displayed on adjacent lines, due to band-width restriction. These effects require further investigation.

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* Post Office Engineering Department Report: An Investigation into the effects of Interference on Television Pictures. Since this paper was written the G.P.O. have carried their work a stage further and the reader is referred to Post Office Engineering Department Report: An Investigation of the Visibility of Noise on Television Pictures.

12. Procedure

Fifteen subjects took part in these preliminary experiments on the visibility of noise in television pictures. It was found convenient to seat five subjects at a time in front of the experimental television screen. Some subjects were, therefore, a little further from the screen than others, but the average distance was approximately four times picture height for one series of observations and eight times picture height for a second series of similar observations.

Each subject was handed a sheet of paper which was divided into four columns headed 'Not Visible', 'Just Visible', 'Just Annoying' and 'Very Annoying'. It was explained to the subjects that the still picture of the University of London Senate House building, which they could see on the screen, was substantially noise-free, but various amounts and types of noise would be added to it. When an example of random noise with a specific power was added to the picture, a number would be called out. If no noise could be seen on the picture, then that number was to be written in the first column headed 'Not Visible'. If some noise could be seen, however, although it did not disturb the viewer unduly, then the number called should be written in the second column, headed 'Just Visible'. If there was sufficient noise present for the viewer to feel it would lower his appreciation of a programme being broadcast, then the number called should be put in the third column headed 'Just Annoying', or finally, if the viewer felt there was a great deal of very disturbing noise he could write the number in the last column, headed 'Very Annoying'. It was emphasized that the numbers called would bear no logical relationship to the type and amount of noise being put into the picture. The viewers were allowed as much time as they desired to decide upon a category for each example given. Seven narrow bands of noise could be isolated from a spectrum of random noise. These were:

1. 0·0 –0·30 Mc/s: mean value 0·15 Mc/s
2. 0·35–0·65 Mc/s: mean value 0·5 Mc/s
3. 0·85–1·15 Mc/s: mean value 1·0 Mc/s
4. 1·35–1·65 Mc/s: mean value 1·5 Mc/s
5. 1·85–2·15 Mc/s: mean value 2·0 Mc/s
6. 2·35–2·65 Mc/s: mean value 2·5 Mc/s
7. 2·70–3·00 Mc/s: mean value 2·85 Mc/s

The level of the noise in any given band could be adjusted by means of a variable attenuator in 1 db steps. After a pilot run with a few subjects, it was found that 2 db steps were usually desirable. The pilot run enabled an approximate idea to be obtained of the attentuation suitable for the output of each noise band which would make the noise 'just visible' to most viewers. This knowledge was used to choose from 7 to 9 steps of attenuation of the output from each noise band. These steps were written down in random order with the aid of a table of random numbers and each attenuation was used twice. Thus between 14 and 18 numbers were written down for each noise band. The seven noise-band centre frequencies were themselves written down in random order. Table 1 is part of the chart with which the experimenter was furnished.

TABLE 1

Part of Chart used by Experimenter

Centre Frequency of Noise Band	Prefix No.	Suffix No. 1	2	3	4	5	
1·0 Mc/s	1	25	27	21	29	27	. . . . . .
0·15 Mc/s	2	32	31	28	31	30	. . . . . .
2·85 Mc/s	3	22	16	14	14	20	. . . . . .

db of attenuation

For example, number 2.3 refers to the 0·15 Mc/s noise band with 28 db attenuation. With the aid of this chart it was possible for the various levels of the noise outputs to be shown to viewers in random order without giving any clue as to the amount of noise being added to the picture. The chart made it easy to read back, in db attentution of noise output, the numbers written on the papers filled in by each subject, an example of which is given in Table 2.

TABLE 2

Example of Paper filled in by a Viewer

Prefix No.	Not Visible	Just Visible (Suffix No.)	Just Annoying (Suffix No.)	Very Annoying
1	4	1, 2, 5	3, etc.	
2	1, 2	4, 5	3, etc.	
3	1	5	2	3, 4, etc.

Reading along the line in Table 2 denoted by the prefix No. 2, we see that for the suffix Nos. 1, 2, 4, 5, and 3, by referring to Table 1, a narrow band of noise centred around 0·15 Mc/s is not visible for 32 db or 31 db, is just visible for 31 db and 30 db and just annoying for 28 db. This is purely an example of how the system is used, rather than an indication of the results actually obtained.

13. Treatment of Results

The results of three batches of five viewers were added together and from their combined answers it was possible with each noise band to calculate the percentage of all occasions on which any particular amount of noise added to the picture was not visible, just visible, etc.

When the percentages had been calculated, the four columns were given weighting values. The first column 'Not Visible', was given factor 0, the second column, 'Just Visible', was given a factor of 1, the third column, 'Just Annoying', received a factor of 2, and the last column 'Very Annoying', a factor of 3. Each percentage value was multiplied by the appropriate factors and the total score obtained with each attentation level was then calculated. If all the viewers decided that a particular value of noise in a given band produced an effect which was 'very annoying' on each occasion that it was presented, that attenuation level would occur as 100 per cent under the 'Very Annoying' column, which has been weighted by the factor of 3, and the total score would thus become 300, the maximum possible score. If all the viewers placed the attenuation level under the heading 'Just Visible', the score would be the 100; and under the heading 'Just Annoying', the score would be 200. A noise attenuated to such a low level that no one ever saw it would score 0.

Figs. 15(a) and 15(b) show the scores derived in this manner plotted at each attenuation level investigated, for the seven noise bands. Fig. 15(a) represents the results when the average viewing distance was approximately four times picture height and Fig. 15(b) when the average viewing distance was approximately eight times picture height. It is noteworthy that doubling the viewing distance (Fig. 15(a) to 15(b)) allows the noise power to be quadrupled for the same threshold to be maintained.

It is, in theory, possible for a score of 100 to be achieved at any one attenuation of noise-level, because all the readings might be placed under the heading 'Just Visible'. In practice, the same score will be achieved in numerous different ways. For example, half the readings may be placed under the heading 'Not Visible', and half under the heading 'Just Annoying', and the score will be (50 per cent × 0 + 50 per cent × 2). It is reasonable to assume, however, that the score 100 is a good indication that on the average a noise is 'just visible' all the time, and from this assumption, if a score of 50 is attained, the noise is, on the average, 'just visible' for half the occasions. The score 50 has been assumed to be representative of the borderline between 'not visible' and 'just visible' and at this score level, represented by a horizontal line in Fig. 15, the values of attenuation of output for each noise band have been taken so as to draw a curve of threshold of visibility in terms of attenuation in db for the seven noise-band mid-frequencies, Fig. 16. Similarly the score 200 has been assumed to indicate a complete certainty that the noise is 'just annoying' and 100 has been taken as the threshold of annoyance. The values of attenuation of output for each noise band at the score level 100 in Fig. 15 have been used to obtain the threshold of annoyance curves, which are shown in Fig. 16.

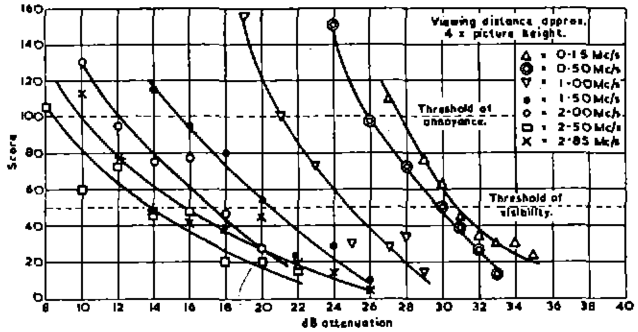

Fig. 15(a) — Relative visibility and annoyance of 7 different bands of noise superimposed on a still picture; plotted in terms of arbitrary scores

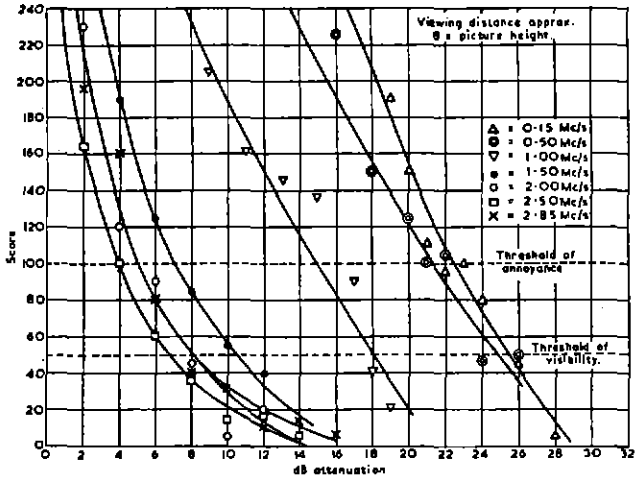

Fig. 15(b) — Relative visibility and annoyance of 7 different bands of noise superimposed on a still picture; plotted in terms of arbitrary scores

14. Analysis of Results

The four curves obtained, namely, threshold of visibility at viewing distances of four-times and eight-times picture height, and threshold of annoyance at these same two viewing distances, are of similar shape and are very roughly parallel to each other. The Post Office Engineering Department carried out a similar investigation, using different methods of assessment, but using only three different noise bands. The three values they obtained are shown in Fig. 16 with the curve drawn through them by the Post Office investigators. Another curve has been sketched through these same three points more or less parallel to the four curves of the present investigation. Thus it can be said that the three isolated points obtained by the Post Office are not inconsistent with the present results. There is insufficient evidence to determine whether they do in fact lie on a similarly shaped curve or on a curve of the type drawn by the Post Office, which is the simplest solution to the type of curve that may be expected when only three points are established.

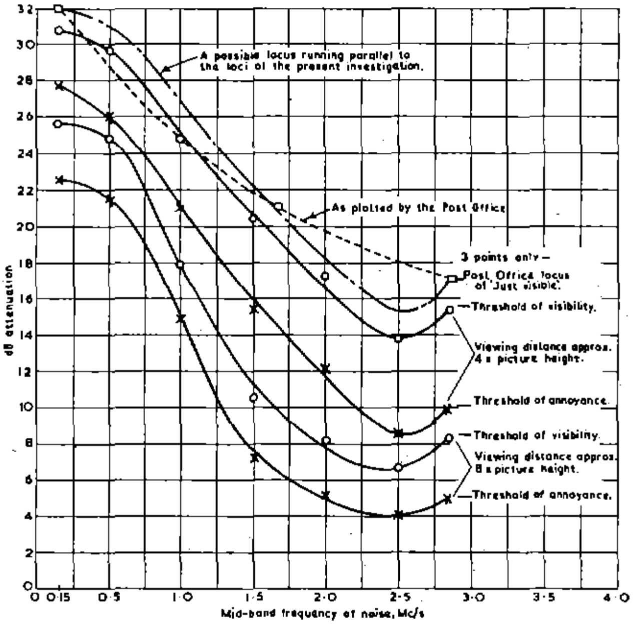

Fig. 16 — Thresholds of visibility and annoyance for 7 different bands of noise superimposed on a still picture

Fig. 16 illustrates that noise tends to become less visible as the centre frequency of the band containing it moves up through the spectrum from 0·15 Mc/s to 2·85 Mc/s. There is, however, a minimum in each of the four curves, at 2·5 Mc/s. It may be argued that, as the centre frequency of a noise band becomes greater, the size of the units in the disturbance pattern it creates on the television screen becomes smaller and, therefore, less visible. This may account for the general trend of the four curves, but does not explain the minimum always occurring at 2·5 Mc/s, because the position of it would be expected to depend on viewing distance. As the two appear to be independent, it is not easy to account for this minimum, unless it is in some way associated with instrumentation.

The curves of threshold of annoyance run parallel to the curves of threshold of visibility and therefore indicate that annoyance is aroused when a noise pattern attains a fairly specific level of visibility above the threshold, of the order of 3 or 4 db, and is more or less independent of the type of noise pattern.

This preliminary work thus establishes the relative visibility of narrow frequency bands of noise situated in the range from 0 to 3·0 Mc/s. It indicates the relationship between the 'visibility' of noise and the 'annoyance value' of noise. The results are not at variance with earlier work carried out by the Post Office Engineering Department.

The foregoing tests do not cover all the experiments necessary to obtain a complete answer to the problem of the dependence of noise visibility upon spectral distribution. In order to complete the investigation it would be necessary to carry out tests on a variety of shapes of noise spectra, and to examine further the cause of the anomalous minima at 2·5 Mc/s in the curves of Fig. 16. It might nevertheless be considered that sufficient information had been obtained to enable a suitable weighting network to be proposed. A caution must, however, be added here and the reader is referred to the remark on page 13: 'There is no *a priori* reason for assuming that the annoyance value of a broad band of noise will be the same as the sum of the annoyance values of a number of smaller bands occupying the same total bandwidth.'

The top curve in Fig. 16 approximates to the function $32\text{–}20 \log_{10}(1 + f^2)$ at least up to 2·5 Mc/s if f is in Mc/s. It will be observed that this is a function of $1/(1 + f^2)$. The latter expression is also the modulus of a transfer function constituted by the product of the transfer functions of two RC de-emphasis circuits. Thus, if noise were measured on a power or r.m.s. basis after passage through two de-emphasis circuits each having the time constant $RC = 0{\cdot}16\mu s$, (the weighting network being such that the impedance of the second circuit had no influence upon that of the first), it might be claimed that the visibility or annoyance of the noise would have been assessed with adequate precision were it not for the above mentioned caveat.

15. Acknowledgments

The author is indebted to Mr C. B. B. Wood for the initial planning of the tests, to Dr D. Maurice for the method of narrow-band variable-frequency noise generation and to Mr E. R. Rout for design and instrumentation.

For a very thorough discussion of noise in television the reader should refer to Schade, O. H., *Electro-Optical Characteristics of Television Systems*. R.C.A. Reviews, March and September, 1948.

PART III

PHOTOGRAPHIC RECORDS OF THE EFFECT OF RANDOM NOISE ON A TELEVISION PICTURE

16. Introduction

For demonstration purposes photographic records of pictures on the screen of a television receiver were required for a range of signal-to-noise ratios. The picture used was the BBC Test Card C; it was generated by a monoscope.

The receiver was of a modern commercial type, with a seventeen-inch rectangular tube. It incorporated an efficient a.g.c. system which enabled small changes of signal-to-noise ratio to be achieved without any appreciable change of contrast, by altering the input-signal amplitude.

17. Definition of the Signal-to-Noise Ratio

The parameter of the input signal quoted in this article is the r.m.s. voltage corresponding to the peak-white condition. The noise voltage is the theoretical r.m.s. value in a 75-ohm source having a bandwidth equal to that of the receiver, multiplied by the receiver noise factor at the appropriate input-carrier amplitude. The receiver a.g.c. altered the gain of the radio-frequency amplifying stage, and as a result the noise factor varied with input-signal amplitude.

Some workers prefer to use d.a.p. (double-amplitude-peak) values. In the case of a video waveform the d.a.p. value is the excursion of voltage between the tips of the synchronizing pulses and the peak-white level of the picture. The ratio of the d.a.p. video signal to the r.m.s. value of the noise, measured at the output of the receiver, is the same as the signal-to-noise ratio quoted in this article.

Various ways of measuring or defining the d.a.p. value of random noise are used. Measurements give a peak-to-r.m.s. ratio of approximately 4*. For a normally distributed noise voltage this corresponds to the value exceeded for one ten-thousandth of the total time, but the only justification for using this as the basis for a definition is that it agrees with the measured values. The ratio of the d.a.p. to the r.m.s. value of random noise may therefore be taken as approximately 18 db. To obtain the d.a.p. signal-to-noise ratio from the values quoted in this article, therefore, 18 db should be subtracted.

18. Photography

The receiver was adjusted to give a high luminance in the peak-white condition, consistent with a good contrast range. The exposure time was set by means of an electronic shutter circuit which brightened the tube face for the duration of either one or two complete pictures, as required; the mechanical camera shutter was left open until after completion of the exposure.

The lens aperture used was f/4·5 and the negatives were made on H.P.3 plates developed for 11 minutes at 65°F. in D163, with a 1:3 dilution. The prints used for the subjective tests were 10 × 8 in. enlargements on Grade 3 paper, and are reproduced herein approximately full-size.

19. Subjective Comparisons

Fifteen observers took part in the subjective comparisons between the photographs and the original pictures. Each was presented with a series of eight photographs, but these were not in an ordered sequence; the signal-to-noise ratio was adjusted until the picture on the screen was judged to correspond most closely with the photograph. The results for an exposure time of 1/25 sec., i.e. the duration of one complete picture, are summarized in Table 3. This shows the mean difference between the apparent and actual signal-to-noise ratios and the standard deviation for each condition, to the nearest 0·5 db. The photographs appear slightly less noisy than the originals, but the mean difference between the apparent and actual signal-to-noise ratios is less than 1 db. The standard deviation increases from about 2 db at low signal-to-noise ratios to 4 db at high signal-to-noise ratios; it is not surprising that the standard deviation increases as the signal-to-noise ratio increases.

The observers in the group comprised twelve engineers, five of whom were experienced in detecting faults in television pictures, and seven not, and three secretarial staff; these categories are referred to as Groups A, B, and C respectively. Table 4 shows the means and standard deviations for the three groups separately. There is a tendency for the mean differences for Group A to be greater than those for the other two groups.

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* A summary of some experimental results is given in *Survey of Existing Information and Data on Radio Noise over the Frequency Range* 1–30 *Mc/s.* D.S.I.R. Radio Research Special Report No. 15, p. 95, published in 1947.

TABLE 3

Exposure time 1/25 sec.

Photograph No.	*Peak white luminance, ft-lamberts*	*Input signal-to-noise ratio, db*	*Subjective results*	
			Mean difference, db	*Standard deviation, db*
1	11	16	—0·5	1·5
2	14	22	0	2·5
3	15	28	1·0	3·0
4	15	31	1·5	4·5

Another series of photographs was taken with an exposure time of 2/25 sec., corresponding to the duration of two complete pictures. The effect of doubling the exposure was to increase the apparent difference between the photograph and the original by an additional 2 db; this is probably because the picture information is coherent from one frame to the next, whereas the noise is not.

20. Conclusions

Photographs 1–4 may be regarded as realistic records of the pictures on the receiver screen for the signal-to-noise ratios shown.

TABLE 4

Photograph No.	*Input signal-to-noise ratio, db*	*Group A*		*Group B*		*Group C*	
		Mean difference, db	*Standard deviation, db*	*Mean difference, db*	*Standard deviation, db*	*Mean difference, db*	*Standard deviation, db*
1	16	−1·0	1·5	—0·5	1·5	—0·5	1·5
2	22	1·0	3·0	—0·5	2·0	—0·5	2·0
3	28	2·5	2·5	1·0	2·5	−1·5	1·5
4	31	3·0	5·0	0	4·0	0·5	3·0

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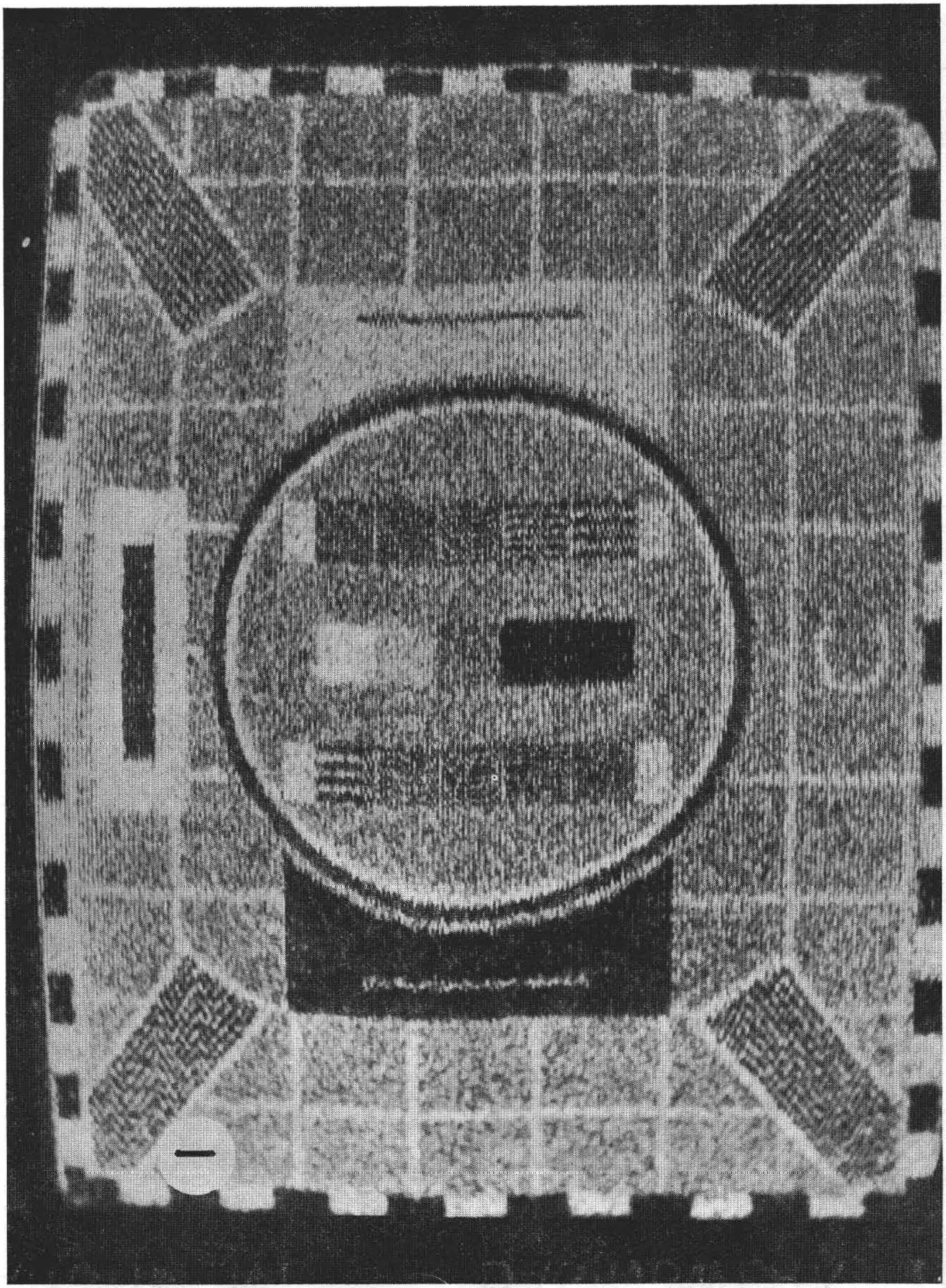

Fig. 1 — R.M.S. signal-to-noise ratio: 16 db. Exposure time: 1/25 sec.

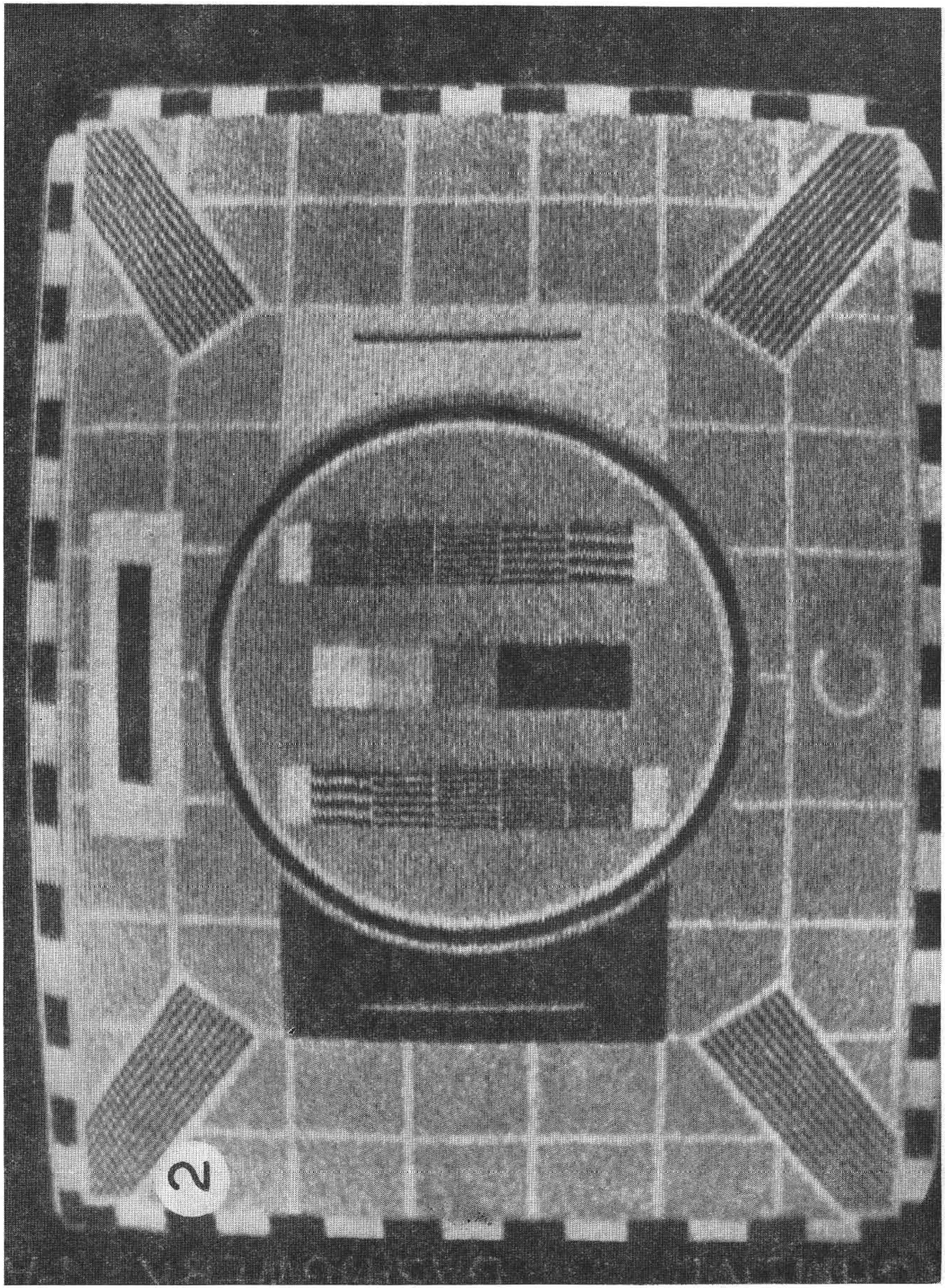

Fig. 2 — *R.M.S. signal-to-noise ratio: 22 db. Exposure time: 1/25 sec.*

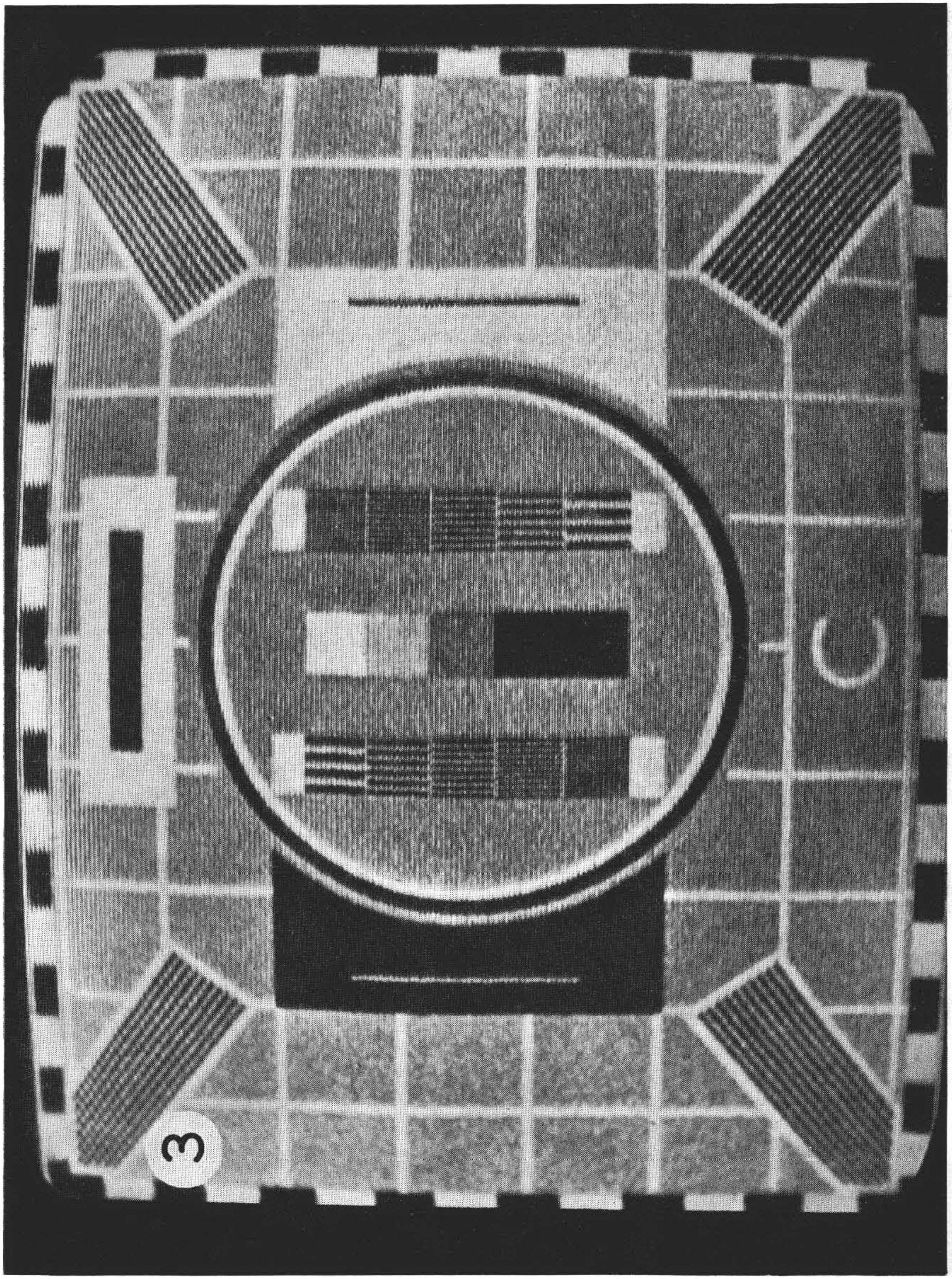

Fig. 3 — R.M.S. signal-to-noise ratio: 28 db. Exposure time: 1/25 sec.

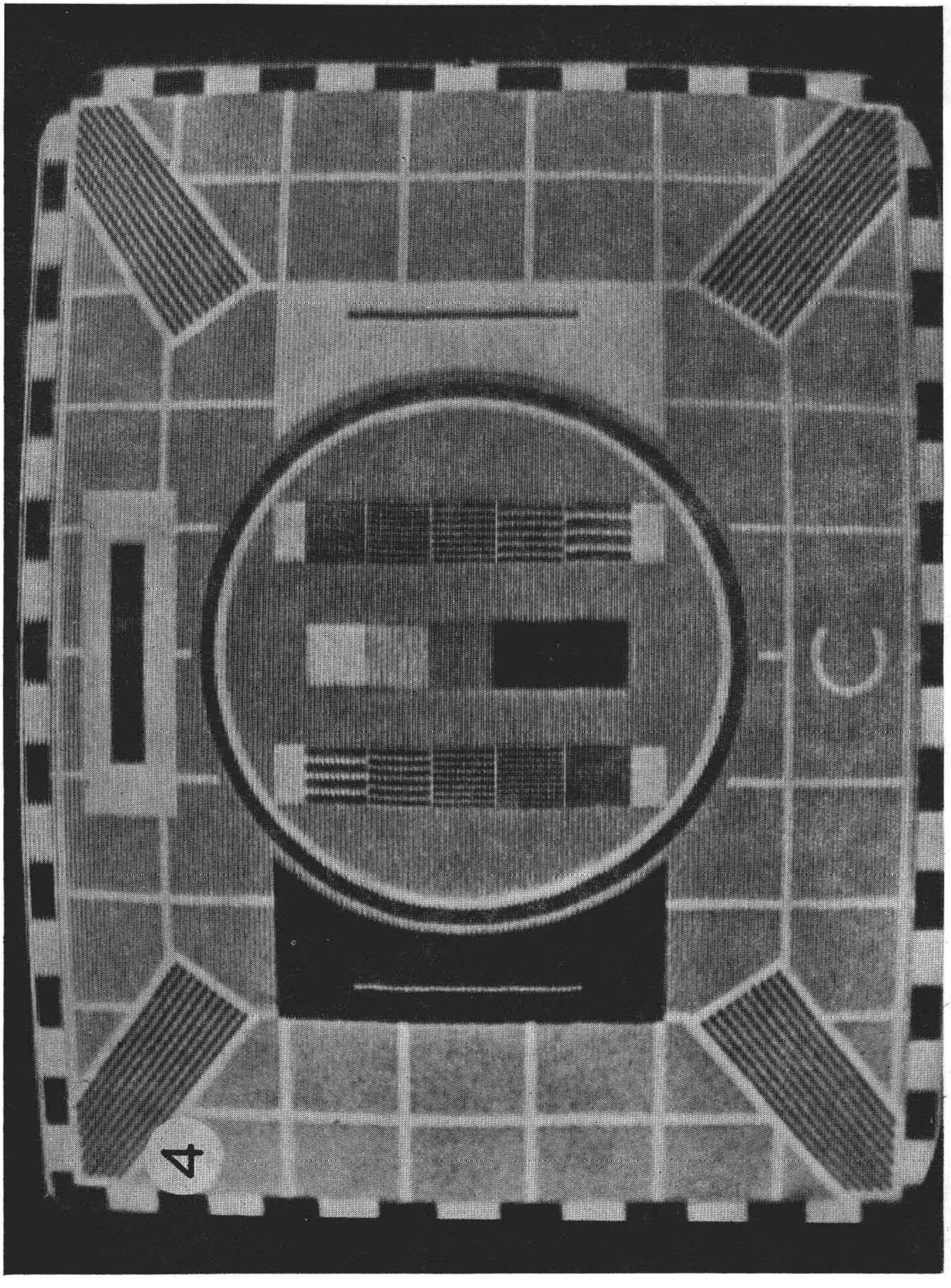

Fig. 4 — *R.M.S. signal-to-noise ratio:* 31 *db. Exposure time:* 1/25 *sec.*

A RECENT BBC DEVELOPMENT IN THE FIELD OF AUDIENCE RESEARCH

AN AUDIENCE REACTION RECORDER

W. A. BELSON AND G. W. DILWORTH

During 1954, in response to a programme need, a device was developed for the moment-by-moment recording of audience reaction to a programme. The main novel feature is that both the programme as viewed or heard *and* the reactions of a group of people to that programme are recorded simultaneously on a single recording medium. This simultaneous recording has two great advantages. It means (i) that the record can be played back to the test group and used as a basis for questioning them as to why they reacted as they did and (ii) that it is immediately available for subsequent detailed study by programme departments.

In the present system the recording medium is a magnetic tape recorder. Members of a test group operate micro-switches (suitably labelled) to indicate their reactions to what they are seeing or hearing. These switches operate, via relays, a simple potentiometer so that the amplitude of a tone (5000 c/s in this case) is varied in accordance with the number of people pressing switches at any time. This tone is then fed to a magnetic recorder; at the same time the sound programme, or the sound associated with the television programme, to which the group is listening is also fed to the recorder via filters. Thus the two sets of signals are simultaneously recorded and are immediately available for synchronized replay. In replaying, the tone is filtered out, rectified, and arranged to operate a suitably calibrated meter, the programme itself being reproduced in the normal way.

It must be emphasized, however, that the system as described is only one of the many methods which could be employed: for example, if the programme were visual and were required to be visual for play-back, the reaction signals could be superimposed on a magnetic tape attached to the film; again, systems employing methods other than variation of tone amplitude could well be used if the need for larger groups or for more detailed information became necessary (the present system deals with groups of only twenty at a time).

It is obvious that before the device can be used generally for programming purposes, validation of the psychological aspects of its use has to be carried out. The BBC Audience Research Department has begun such a programme of validation and the results of the preliminary checks so far made are reassuring.

It is suggested that the device be called the Audience Reaction Recorder. It probably has its greatest potential value where the production is a trial one, or where editing (of film or of sound track) is planned, for by its use less effective spots can be located. But even when the reaction recording procedure is used on the final production—that is, as broadcast—there may still be something to be learned, especially if the programme is one of a series. While use of the device has so far been restricted to the study of light entertainment material, there seems to be no reason why it cannot be used for some other types of programme. It will be obvious that a device of this kind is not limited in its application to material intended for broadcasting.

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